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Persistence of Trace Metals in Shallow Arctic Marine Sediments Contaminated by Drilling Effluents*

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ABSTRACT

Offshore oil exploration activity usually requires the discharge of drilling muds and formation cuttings into adjacent waters or on ice above these waters. Although dispersal of these muds is well documented in marine environments of moderate to high energy, the fate of drilling muds in shallow, low-energy Arctic environments has received little attention. This study focused on three drilling effluent disposal sites around Stefansson Sound in the Alaskan Beaufort Sea. All sites were in shallow (less than 5 m), low-energy marine environments. Sediment concentrations of six metals often present in drilling effluents (aluminum, arsenic, barium, chromium, lead and zinc) were examined. Metal concentrations obtained from replicate grab samples along 100 m transects were compared with those taken at four shallow-water offshore island control sites, and with data from other studies.

The results indicate persistence of barium, chromium, lead and zinc at certain stations at all three discharge sites, and elevated concentrations of aluminum at one of the three sites when sampled 2–4 years after the discharges. Metal concentrations, when elevated, were typically highest near the discharge points, continued in the direction of wind-induced longshore

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transport, and generally diminished with distance from the discharge site. However, distributions displayed some patchiness indicative of in-place melting of ice-rafted muds or reworking of sediments by currents or ice-gouging.

Further work will be needed to evaluate the biological impacts of drilling effluents. However, the slow dispersal of these materials suggests there is a need for closer evaluation of drilling effluent persistence problems at shallow, low-energy locations in the Beaufort Sea.

INTRODUCTION

The physical fate and biological effects of drilling effluents (including continuous and bulk discharges of drilling fluids, whole muds, and formation cuttings) from offshore oil and gas exploration have been subjects of considerable controversy (API, 1980; Neff, 1981; NRC, 1983). The National Research Council concluded that dispersion of drilling fluids and formation cuttings is high, and that toxic effects are unlikely at typical continental shelf depths. However, the National Research Council acknowledged a paucity of data on the physical fate of drilling effluents in low-energy environments.

Several Beaufort Sea studies have attempted to address this problem. Northern Technical Services (NORTEC, 1981) examined drilling effluent dispersal and biological effects at Reindeer Island and at sites offshore from the Sagavanirktok River Delta. At these sites, high-volume river flow and the rafting away of ice floes in early summer dispersed effluents, and no persistence of metals was detected. In a second study by NORTEC (1982) at other delta locations and at Challenge Island to the east, the results were more difficult to interpret. In the delta, high variability of metal concentrations in sediments, and post-discharge sediment samples with lower metal concentrations than pre-discharge sediment samples, were frequently found. The investigators attributed these findings to the naturally high variability expected at the mouth of a major river. However, at Challenge Island, a site removed from high river discharge, concentrations of cadmium, chromium, copper, lead and zinc increased after the discharge of drilling effluents.

Most Beaufort Sea nearshore areas not subject to large river discharges, over-ice flows ('overflows'), or flooding at breakup can be considered low-energy environments. Shoreward of the 2 m isobath, the water column generally freezes to the sea floor in winter (Barnes & Reimnitz, 1974). Outside this boundary, for the 8–9 months of ice cover, current velocities are frequently an order of magnitude lower than during the brief open-water season (Wiseman *et al.*, 1974). Nearshore mean flows of under-ice currents are generally less than 2 cm/s, although actual current velocities may reach 5–9 cm/s (NORCOR Engineering and Research, Ltd, 1975; Kovacs & Morey, 1978; Matthews, 1981*a,b*; Aagaard, 1984). In contrast, wind-driven currents reach or exceed 15 cm/s after ice breakup, with episodic events resulting in currents of up to 25 cm/s in open-water nearshore areas (Barnes & Reimnitz, 1974; Aagaard, 1984). Detailed monitoring in the Prudhoe Bay vicinity suggests a similar pattern in current speeds with mean winter currents of less than 2 cm/s at all depths (Mangarella *et al.*, 1979) and mean summer currents of approximately 12–15 cm/s (Britch *et al.*, 1983). Lower current velocities and wave energies may occur along shorelines protected from prevailing easterly and east-northeasterly winds, such as on the lee side of barrier islands.

This investigation was prompted by inadequate information on dispersal of drilling effluents in sheltered marine environments, together with field observations suggesting that effluents were not dispersing from several well sites. As of 1985, approximately 35 exploratory wells had been drilled in the shallow nearshore zone of the Alaskan Beaufort Sea, either from natural barrier islands or from artificially constructed gravel islands. Most of these were deep wells (3600–4300 m) and involved relatively large quantities of drilling muds and fluids (640–900 t/well) (Jones & Stokes Associates, Inc., 1983*b*; Cooper Consultants, Inc. & Envirosphere Co., 1987). Estimated concentrations of trace metal constituents in typical effluents are shown in Table 1.

Arsenic, barium, chromium, lead, zinc and aluminum were selected for analysis in this study. Barium, chromium, lead and aluminum are generally considered to be good indicators of the presence of drilling

TABLE 1

Expected Trace Metal Concentrations (Particulate) from Drilling Effluent from a 166 100-kg Discharge Released at 1 000 bbl/h in 5 m of Water with a Current of 10 cm/s (After Jones & Stokes Associates, Inc., 1983*a*)

	Metal (mg/kg)				
	As	*Ba*	*Cr*	*Pb*	*Zn*
Discharge	24	141 000	1 300	820	400–1950
30·4 m from discharge	0·05	404[a]	87[a]	1·7	100[a]

Data on aluminum were not available.

[a]Assumed sediment background concentration of authors used when dilution to less than background concentration computed.

effluents (Kahlil, 1980; Chow & Snyder, 1980; Gettleson & Laird, 1980; NRC, 1983). Zinc and arsenic may also be good indicators, since concentrations of these metals in barite deposits may be elevated 10–100 times (Kramer *et al.*, 1980). All six metals have been found in elevated concentrations in certain Prudhoe Bay reserve pits, as well as in tundra wetland effluent discharge sites (West & Snyder-Conn, 1987; Woodward *et al.*, 1988). Arsenic was found by Crippen *et al.*, (1980) to be associated with the barite component of drilling mud used in offshore drilling in the Canadian Beaufort Sea. However, arsenic has also been found at elevated levels in anadromous and estuarine fish from Beaufort Lagoon (West, 1986), indicating naturally high concentrations in marine sediments near the mouth of at least one major stream on the Beaufort coastline.

Sediment samples from three exploratory well sites (Cross, Alaska, and Goose Islands) and four control sites (Fig. 1) were analysed for the trace metals indicated previously. The null hypothesis tested is that drilling effluents do not persist for more than 1 year as a result of discharges of drilling wastes from oil exploration in the nearshore zone at shallow, low-energy Arctic island sites.

SITE DESCRIPTIONS

Cross Island

Cross Island (70° 29′ 30″N, 147° 58′ 56″W), a proposed National Landmark, is a crescent-shaped natural barrier island 3·2 km long and 400 m wide, located 18 km north of the Sagavanirktok River Delta immediately east of Prudhoe Bay. Its sand and gravel substrate is sparsely vegetated with forbs and grasses. The island supports the largest known nesting colony of common eider (*Somateria mollissima*) in the Alaskan Beaufort Sea (222 active nests in 1985), is often used by denning polar bears (Lentfer, 1976), and is a traditional Eskimo subsistence hunting and whaling site (AEIDC, 1979). Part of the 'Boulder Patch', a unique rocky subtidal community (Dunton *et al.*, 1982), lies approximately 3 km southeast of Cross Island (Reimnitz & Ross, 1979).

Exploration drilling by Tenneco and Gulf Oil Companies began on the island in 1983 and ended in the winter of 1984. Drilling effluents were discharged on ice and in open water 2–3 m deep, off a gravel pad constructed on the southwestern tip of the island. While there was deeper (6–8 m) water immediately seaward, the disposal site was protected from the prevailing northeasterly winds. Secondary westerly and south-

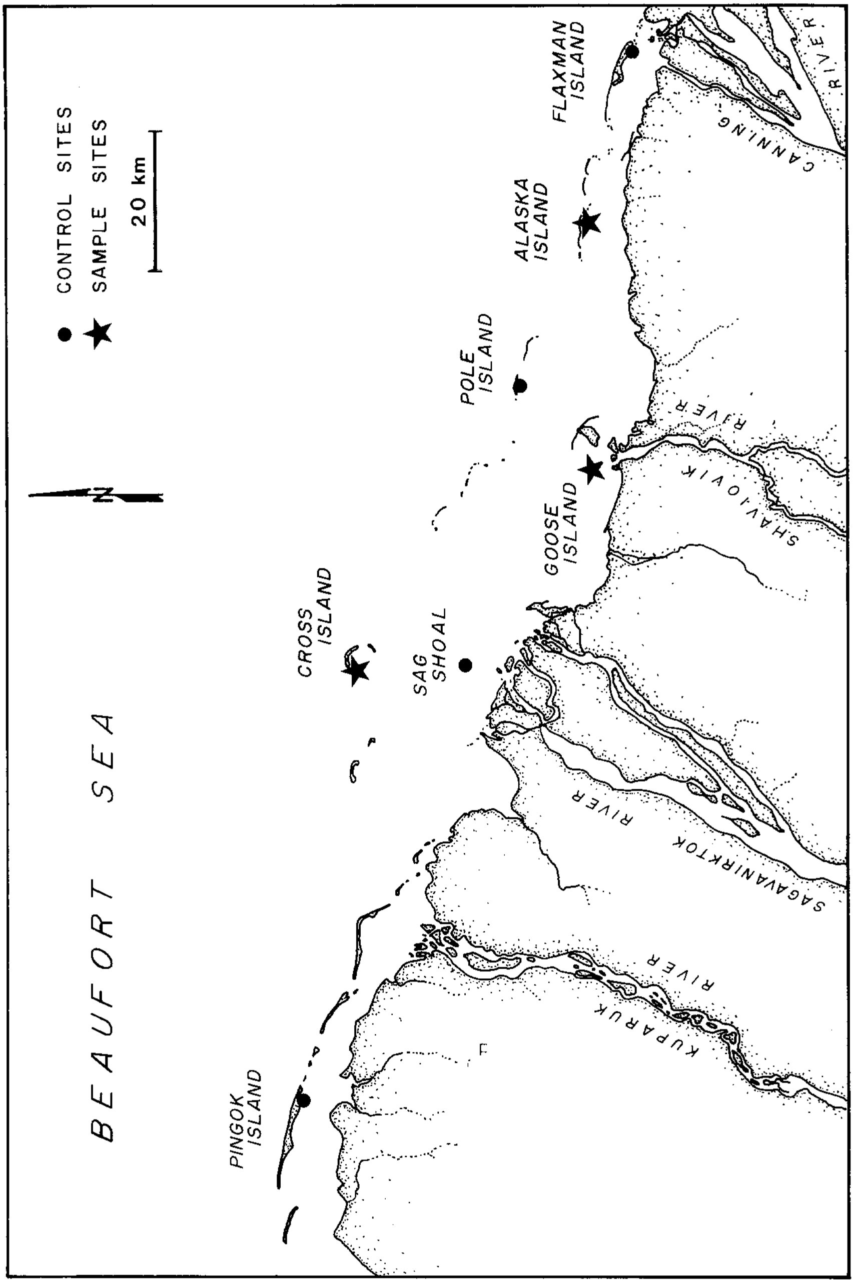

Fig. 1. Three shallow-water, low-energy drilling effluent discharge sites and four control sites sampled in the Beaufort Sea, Alaska.

westerly wind events would tend to push the drilling wastes shoreward, causing their retention. Longshore transport appeared to have carried a significant portion of this material a short distance to the southwest. Discharged effluents were observed to persist at this site through the entire 1984 open water season as a mound rising more than 1 m above sea level.

Alaska Island

Alaska Island (70° 13′ 46″N, 146° 29′ 58″W) is one of four unvegetated, sand/gravel, natural barrier islands in the Maguire Islands group, east of Prudhoe Bay. This low-lying island is approximately 4 km long and 50–100 m wide, oriented in an east-west direction. It is approximately 6 km north of the mainland, and supports a sizable common eider breeding colony (30–40 nests in most years). Exploratory drilling by SOHIO Alaska Petroleum Company occurred on the eastern end of the island from November 1981 to May 1982. The US Army Corps of Engineers Section 404 permit at this site required backhauling and onshore disposal of fluids and cuttings at an approved site before breakup. However, this requirement was later waived, and effluents were discharged both on ice and in the shallow (1–2 m) water adjacent to the drill site. The disposal site was on the shallow lagoon side of the island, where the wave and current climate is relatively benign. Formation cuttings, suspended fluids, and evidence of hydrocarbon spillage were observed at the site after ice breakup in July 1982.

Goose Island

Goose 'A' Island (70° 13′ 04″N, 147° 20′ 44″W) is a circular artificial gravel island built in 1982 by Shell Oil Company. The 152-m-diameter island is located in 1·5 m of water in Foggy Island Bay about 1 km north of the Shaviovik River Delta and 2·4 km west of a large natural island (Tigvariak). Hence, it receives some protection from strong easterly and northeasterly winds, and resulting west-flowing currents. Over-ice flooding from the Shaviovik River during breakup enhances dispersal and reworking of marine and fluvial sediments. State and Federal permits stipulated backhauling of the drilling effluent to approved onshore disposal sites. Even so, drilling effluents were discharged on sea ice around the island during the winter of 1982–83. After breakup in 1983, effluents were observed on grounded ice and standing in open water to the east, south, and southwest of the island.

Control sites

Four control sites were sampled. Three sites were located on the south sides of nearby islands with no known history of offshore drilling effluent disposal and were located: (1) just south of the eastern end of Pole Island (70° 18′ 30″N, 147° 04′ 00″W) at a depth of 3 m; (2) 15 m south of the eastern end of Flaxman Island (70° 11′ 44″N, 146° 58′ 00″W) in 1·2 m of water; and (3) 180 m south of the eastern end of Pingok Island (70° 33′ 45″N, 149° 30′ 20″W) in 1–1·2 m of water. A fourth control site, on a shoal 3·2 km north of the Sagavanirktok River Delta, was located between Endeavor and Resolution Islands (70° 22′ 00″N, 147° 59′ 00″W), two artificial drilling islands in water 1·2 m deep. This site is subject to extensive overflow and flooding from the Sagavanirktok River, and earlier studies (NORTEC, 1981; 1982) had detected no trace of drilling effluents.

MATERIALS AND METHODS

Sediment samples were collected between 26 July and 21 August 1985, from a 7 m US Fish and Wildlife Service (USFWS) vessel. At each island where drill muds and cuttings had been discharged, three to four transects radiating from the approximate discharge point were established. Five stations at approximately 25-m intervals were sampled along each transect. Two replicate samples were taken while anchored at each transect station and at each of four reference sites. At Alaska Island, two replicate samples were also taken from bagged cuttings used as slope protection. A brass Ekman dredge (3540 cm^3 in volume) was used to sample bottom sediments. Due to the gravelly nature of the substrates, only surficial sediment (to approximately 15 cm depth) was obtained, and several grabs were typically required to obtain a sample. Portions of each grab not in contact with the dredge itself were transferred to a polyethylene tray, homogenized using a polyethylene cylinder, and then subsampled after removal of gravel with stainless steel forceps. Between samples, the dredge and implements were rinsed thoroughly in seawater to minimize contamination. Samples were stored in 500-ml wide-mouth polyethylene bottles that had been acid-rinsed and cleaned according to standard methods (APHA *et al.*, 1981) for metals sampling. Samples were maintained at near-freezing ambient temperatures in the field, and were subsequently frozen and shipped by air to the US Environmental Protection Agency's (EPA) Manchester, Washington analytical facility. Samples were kept frozen until analysis.

Sample preparation, analyses, and quality control procedures followed those prescribed by the EPA (1982*a*) Method 3010 for solid wastes. A Perkin–Elmer Model 5000 Zeeman atomic absorption (AA) spectrophotometer equipped with a computerized digital printout was used for the analyses. For arsenic, graphite furnace AA procedures were followed. Other metals were analysed by AA using a nitrous oxide acetylene flame. Unfortunately, funding constraints precluded additional analyses of grain size fractions. However, it is believed that the level of analysis employed is sufficient to determine the persistence of elevated heavy metal concentrations in areas of known contamination.

RESULTS

Trace metal concentrations at reference sites and at drilling effluent discharge sites are summarized in Tables 2 and 3. Specific metal distributions are depicted graphically in Figs 2–7.

Aluminum

Aluminum concentrations for reference sites ranged widely, from 2170 to 5090 mg/kg dry weight. It was not possible to locate any other baseline

TABLE 2
Metal Concentrations in Replicate Sediment Samples at Four Reference Sites in the Nearshore Beaufort Sea, Alaska, August 1985

	Concentration (mg/kg dry weight)					
Sample location	*Al*	*As*	*Ba*	*Cr*	*Pb*	*Zn*
Pole Island	4540	4·7	48	10·5	2·2	47·2
	5260	4·5	74	11·0	1·6	51·8
Pingok Island	2170	2·0	56	3·8	0·1	19·7
	2220	2·1	23	5·0	0·6	19·8
Flaxman Island	3670	2·4	46	8·7	0·1	31·4
	5090	4·5	69	9·0	0·4	54·9
Sagavanirktok	3300	4·1	39	6·4	0·1	51·8
Shoal	3590	4·5	55	5·7	0·1	44·5
Mean	3370	3·6	51	7·5	0·6	38·7
Standard Deviation	1181	1·2	16	2·6	0·8	13·7

TABLE 3
Mean Metal Concentrations and Ranges at the Three Discharge Sites in Comparison to the Mean Concentration and the 95% Upper Confidence Level (UCL) for Reference Sample Sites

Site	*Statistic*	Concentration (mg/kg dry weight)					
		Al	*As*	*Ba*	*Cr*	*Pb*	*Zn*
Cross Island	$\bar{x}$[a]	5 877	4·0	1 809	92	24·4	136
	Range[b]	1 475–13 000	2·8–5·2	778–5 015	5–331	ND–74·5	16–359
Alaska Island	$\bar{x}$	3 124	3·8	1 977	9	8·6	52
	Range	1 870–5 950	2·6–5·0	770–6 605	4–20	ND–33·2	22–150
Goose Island	$\bar{x}$	4 746	5·2	90	11	0·9	58
	Range	3 615–7 265	3·6–7·2	23–344	8–18	ND–6·4	43–97
References	$\bar{x}$	3 730	3·6	53	8	0·6	39
	95% UCL	5 968	5·9	83	12	2·2	65

ND = none detected.
[a]Mean concentration for all stations and all transects by island.
[b]Range of concentrations by island based on average values at each sample station from replicate sampling.

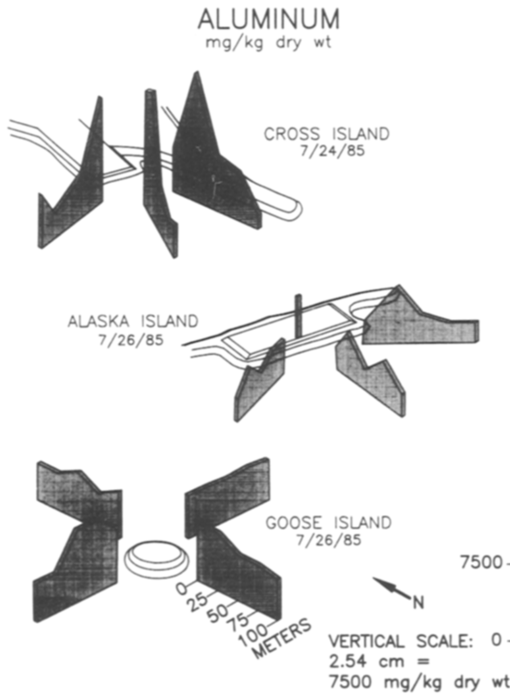

Fig. 2. Mean aluminum concentrations in sediment samples along transects at drilling effluent discharge sites in the Beaufort Sea, Alaska. Islands are not drawn to scale.

data on aluminum in shallow Beaufort Sea sediments. However, these values are low compared to aluminum concentrations in tundra pond sediments from Prudhoe Bay ($\bar{x}$ = 8706 mg/kg, SD = 1467 mg/kg) (Woodward *et al.*, 1988). The high variability in concentration is consistent with findings on aluminum distribution in the Norton Sound region (Larsen *et al.*, 1985). Mean aluminum concentrations in samples obtained from discharge sites are depicted in Fig. 2. Goose Island and Alaska Island concentrations generally fell within the range found at control stations, as did the formation cuttings sample from Alaska Island. However, at Cross Island, mean concentrations ranged as high as 13 000 mg/kg, more than three times the reference mean (3730 mg/kg).

Arsenic

Reference arsenic concentrations ranged from 2·0 to 4·7 mg/kg. We have no other source of baseline data for arsenic levels in nearshore Alaskan Beaufort Sea locations. Crippen *et al.* (1980) reported a baseline concentration from four Mackenzie River Delta sediment samples of 9·9 mg/kg. This value is quite high in comparison to our controls, but still in the range of values for uncontaminated bottom sediments (Moore & Ramamoorthy, 1984). Compared to the arsenic concentrations at control sites, mean arsenic concentrations at discharge sites (Fig. 3) ranged from 2·6 to 5·0 mg/kg at Alaska Island; 2·8 to 5·2 mg/kg at Cross Island; and 3·6 to 7·2 mg/kg at Goose Island. At Alaska Island, the sample of cuttings left on the island contained mean concentrations of 7·6 mg/kg. In general, the concentrations at all three discharge sites fell within the range found at reference sites. A few slightly elevated values occurred at Goose Island, particularly to the south and west.

Barium

Mean barium concentrations at reference sites were one to two orders of magnitude lower than preconstruction concentrations measured by NORTEC (1982) at Endeavor Island, but were closer to the mean barium concentration of 135 mg/kg at Tern Island measured prior to construction (NORTEC, 1983). They ranged from 23 to 74 mg/kg. There is often a wide variation in barium values obtained by various analytical techniques,

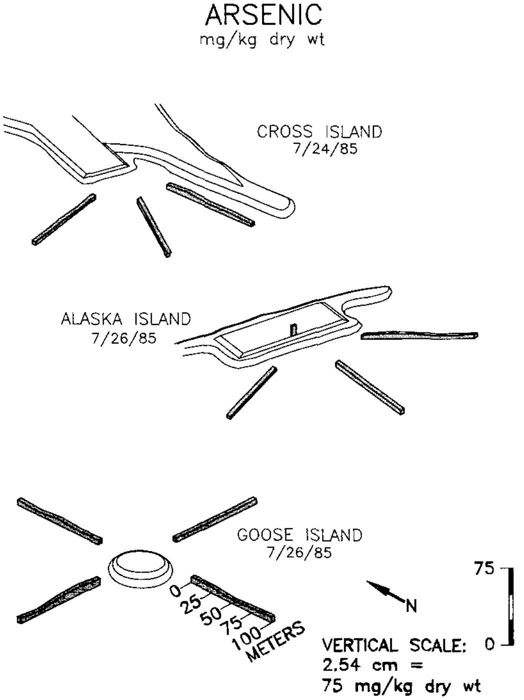

Fig. 3. Mean arsenic concentrations in sediment samples along transects at drilling effluent discharge sites in the Beaufort Sea, Alaska. Islands are not drawn to scale.

and the method used here (AA with nitrous oxide acetylene flame) is probably less sensitive than others. Figure 4 shows that mean barium concentrations along the Alaska and Cross Island transects greatly exceeded concentrations found at control sites, and that Goose Island also exhibited a significant increase over reference sites. At Alaska Island, concentrations ranged from 420 to 6605 mg/kg (the latter, an 89-fold increase over the highest control); at Cross Island, from 445 to 5015 mg/kg (the latter, a 68-fold increase over the highest control); and, at Goose Island, from 23 to 344 mg/kg (the latter, a more than 4-fold increase over the highest control). The drill cuttings sample from Alaska Island had a barium concentration of 3630 mg/kg. The highest barium concentrations at Cross Island were clustered near the discharge and on the alongshore southeast transect. At Alaska Island, the highest concentration was near the discharge point on the southwest transect. As at Cross Island, elevated concentrations occurred on all three transects. At Goose Island, concentrations were an order of magnitude lower than at the other two islands; however, most samples along the south and west transects exceeded the reference mean by 2–7 times.

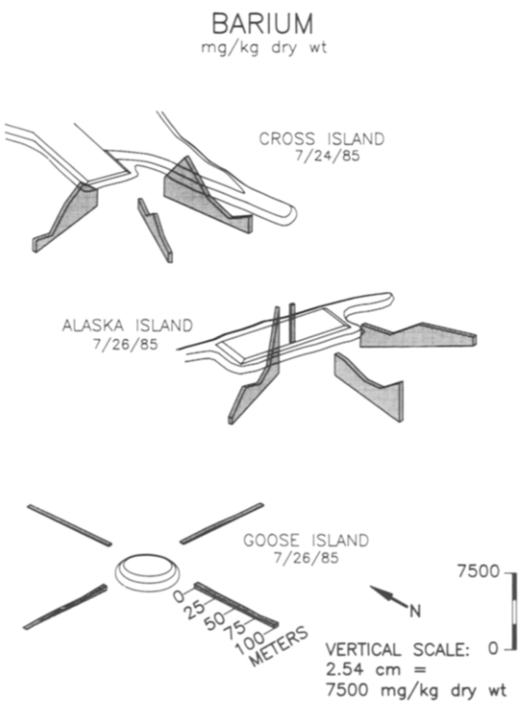

Fig. 4. Mean barium concentrations in sediment samples along transects at drilling effluent discharge sites in the Beaufort Sea, Alaska. Islands are not drawn to scale.

Chromium

Control chromium concentrations ranged from 3·8 to 11·0 mg/kg, and are in general agreement with those of NORTEC (1982), whose various mean concentrations ranged from 2 mg/kg for the north side of Challenge Island to 8 mg/kg for Resolution Island prior to drilling. Figure 5 shows the distribution of chromium at the three discharge sites. At Alaska Island, mean chromium concentrations ranged from 4 to 20 mg/kg, compared to 4 to 11 mg/kg at control sites. The highest concentrations were measured along the southern transect. The cuttings sampled at this island had a mean concentration of 24 mg/kg. Much higher concentrations were encountered at Cross Island, with mean values ranging from 5 to 331 mg/kg, the latter value representing a 30-fold increase over the highest background level of any control sample. The highest concentrations here were clustered around the discharge site and alongshore to the southeast. Concentrations at Goose Island (8–18 mg/kg) were much closer to the controls, but slightly elevated at certain stations, with the highest values along the west and south transects.

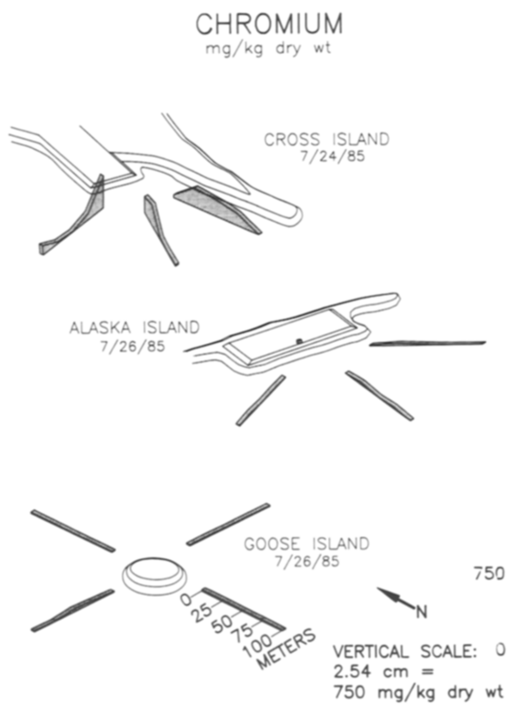

Fig. 5. Mean chromium concentrations in sediment samples along transects at drilling effluent discharge sites in the Beaufort Sea, Alaska. Islands are not drawn to scale.

Lead

The lead concentrations at our reference sites were relatively low compared to preconstruction levels reported by NORTEC (1982) for Endeavor Island and the Sagavanirktok Delta ($\bar{x}$ = 14·8 mg/kg), Resolution Island ($\bar{x}$ = 15·2 mg/kg), and north and south Challenge Island ($\bar{x}$ = 2·5 and 5·2 mg/kg, respectively). The lead values were also low relative to those of Tern Island (NORTEC, 1983). However, compared to control concentrations, lead values at the three discharge sites were high (Fig. 6). Mean concentrations at Alaska Island ranged from undetectable to 33·2 mg/kg; at Cross Island, from undetectable to 74·5 mg/kg; and at Goose Island, from undetectable to 6·4 mg/kg. The drill cuttings sample at Alaska Island had a mean concentration of 12·4 mg/kg. At this island, values were highest along the south and southeast (alongshore) transects. At Cross Island, the highest concentrations were clustered around the disposal site on all three transects. Concentrations were also high on the southeast (alongshore) transect. Two sites closest to the discharge site at Cross Island had concentrations representing a more than 33-fold

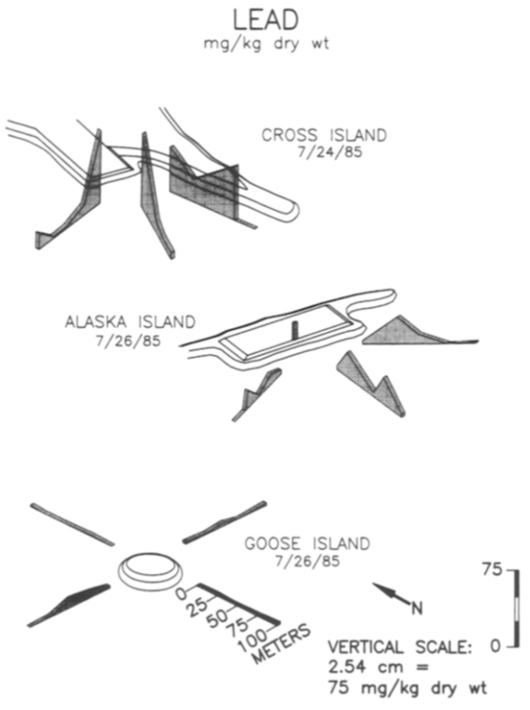

Fig. 6. Mean lead concentrations in sediment samples along transects at drilling effluent discharge sites in the Beaufort Sea, Alaska. Islands are not drawn to scale.

increase over the highest background concentration measured. Goose Island lead concentrations were lower than at the other exploration sites, with the only elevated values (4·2 and 6·4 mg/kg) occurring along the west transect.

Zinc

Control zinc values ranged from 20 to 55 mg/kg, and are in close agreement with the concentrations (16 to 48 mg/kg) reported by NORTEC (1982). The mean concentrations of zinc adjacent to the three exploration sites are shown in Fig. 7. Sediments high in zinc (up to 150 mg/kg) were found at Alaska Island, particularly along the south transect, but also scattered along the remaining transects. The cuttings sampled at this site had a zinc concentration of 95 mg/kg. At Cross Island, even higher concentrations, up to 359 mg/kg (6·5 times more than any control), were found, particularly in the immediate vicinity of the disposal site and alongshore to the southeast. Goose Island concentrations were also slightly elevated, ranging from 43 to 97 mg/kg, with the highest concentrations along the south and west transects.

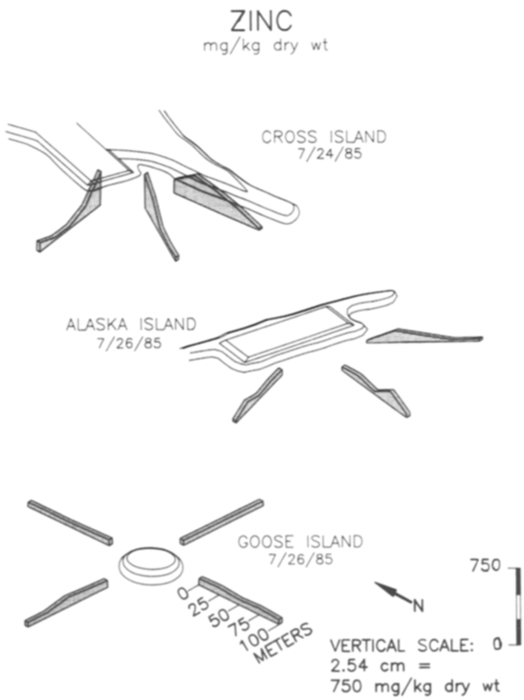

Fig. 7. Mean zinc concentrations in sediment samples along transects at drilling effluent discharge sites in the Beaufort Sea, Alaska. Islands are not drawn to scale.

DISCUSSION

Aluminum and arsenic concentrations were not consistently elevated in sediments near the drilled islands, although aluminum concentrations were highly elevated nearest the Cross Island disposal site, and arsenic concentrations were somewhat elevated in several samples at Goose Island. The lower concentration of aluminum elsewhere may be attributed to lower use of the aluminum stearate compound in the drill mud (NRC, 1983) and/or to the light weight of most aluminum compounds, enabling their rapid dispersion. The finding of elevated arsenic levels only at Goose Island may have resulted from one or more factors: (1) a different source of barite used at this drill site, which may have contained high arsenic concentrations (Crippen *et al.,* 1980); (2) high arsenic concentrations in the formation cuttings (relatively high concentrations appeared in the cuttings sampled at Alaska Island, but these may have been contaminated by drilling fluids); and (3) naturally high concentrations, since the island is in shallow water at the mouth of a large stream where other metals have been demonstrated to concentrate (Boehm *et al.,* 1985).

High concentrations of four other drilling effluent indicator metals (barium, chromium, lead and zinc) relative to reference sites were detected in this study. At all three drill sites, there was a higher concentration of indicator metals at stations nearest the disposal sites.

The coarse fractions (i.e. whole muds and formation cuttings) of drilling effluents may retard dispersion to some extent at the site of disposal. Barium concentrations were consistently higher at all three drill sites than at reference sites, as denoted by mean values for all stations sampled at an island versus the calculated 95% upper confidence level for reference sites (Table 3). Chromium, lead and zinc concentrations were consistently higher at Cross Island than at reference sites, and lead was also consistently higher at Alaska Island than at reference sites. Sporadically high concentrations of chromium and zinc at Alaska and Goose Island sample stations also indicate some retention of metals at certain transect sites. The patchy distribution of contaminated sediments observed along transects at many sample locations appears to be a function of ice-rafting (after on-ice disposal or bottom-freezing) and reworking of shallow sediments by currents and ice gouging. These forces have been observed to cause significant local alteration of shallow nearshore sediments along Beaufort Sea barrier islands (Barnes & Reimnitz, 1974; Hopkins & Hartz, 1978).

Concentrations of lead, chromium and zinc in samples taken near the discharge site at Cross Island were far higher than 'representative metal compositions' of drilling fluids (NRC, 1983) or predicted concentrations based on calculated minimum dilution modeling (Jones & Stokes Associates, Inc., 1983*a*). However, the levels resemble those of whole drill muds sampled at the nearby Reindeer Island stratigraphic test well disposal site (NORTEC, 1981) and are similar to many of the whole effluent solid phase compositions measured at the Endeavor, Resolution, and Challenge Island wells (NORTEC, 1982). The chromium concentrations fall within the range of bottom-weighted drill muds used in Arctic offshore exploration (Hrudey, 1979). The disparity between 'typical' values and those seen in this study can thus be explained by the fact that wells in the Alaskan Arctic are usually deep (from about 2500 m to more than 4200 m), and require the use of proportionally more lignosulfonate drilling fluids and less potassium chloride based muds than necessary for shallow wells. The higher concentrations measured at Cross Island may be a function of the timing of disposal and highly protected location of this discharge point, as well as to more recent activity here than at the other two islands.

There was a general tendency for indicator metals to be clustered near the discharge points. At the two natural islands, high concentrations also occurred alongshore to the southeast, indicating some dispersion by longshore transport. Westward tranport was clearest at Goose Island, a small artificial island least protected from currents driven by the prevailing easterly winds (Barnes & Reimnitz, 1974). Other differences between sites may be attributed to the specific drilling fluids used, initial disposal conditions, site-specific differences in dispersion rates and oceanographic conditions, and solids concentrations in the discharge.

Of particular concern are the high levels of chromium, lead and zinc at the Cross Island site, and the high concentration of lead at the Alaska Island site, since these metals not only serve collectively as tracers of drilling effluents, but may also be acutely or chronically toxic (EPA, 1980, 1985*a,b;* Eisler, 1986). In comparison to controls, or even contaminated sediments elsewhere (Moore & Ramamoorthy, 1984; Varanasi *et al.,* 1988), the concentrations at several Cross Island stations were quite high. For example, in the National Benthic Surveillance Project on the Pacific Coast (Varanasi *et al.,* 1988), which sampled 31 sites, the highest concentrations of chromium found were at San Pablo Bay in San Francisco Bay (455 mg/kg) and at Bodega Bay (380 mg/kg). Lead levels at several Cross Island stations also approached the highest values found in the National Benthic Surveillance Project. These occurred at Long Beach (115 mg/kg) and San Diego Bay (59–82 mg/kg).

Chromium from used chrome and ferrochrome lignosulfonate drilling fluids has been found to bioaccumulate in grass shrimp when the sediment concentration was only 0·248 mg/kg (Carr *et al.*, 1982), and massive cuticular lesions in crabs, lobsters and shrimp at the New York Bight have been shown to be related to sediment chromium concentrations above 100 mg/kg (Doughtie *et al.*, 1983). In process wastes from Arctic offshore exploration, chromium-rich bottom weighted muds have also been found to show much higher acute toxicity in general than surface-hole potassium chloride based muds, or muds used at intermediate depths (Hrudey, 1979).

There is frequently a linear correlation between sorption of lead by invertebrates and its concentration in sediments (Moore & Ramamoorthy, 1984), while uptake by fish and bird species may be variable. In birds of prey and mammals, lead poisoning is a documented cause of nephrotoxic and neurotoxic effects leading to death (EPA, 1982*b*). Lead also poses a threat because of its ability to compete with other essential components of enzyme systems (Bowen, 1966). However, biomagnification of lead is not likely (Kay, 1985; Niethammer *et al.*, 1985) so its toxic effects are probably localized. Nevertheless, this may still be of some concern, since barrier islands or beaches which support exploratory drilling are also important nesting sites for marine birds, such as the common eider, which feed on the benthic infauna of adjacent shallow waters.

The concentrations of zinc in sediments at Cross Island indicate moderate to heavy contamination by this metal, with concentrations comparable to, or higher than, those encountered at other industrial sites, but lower than concentrations measured at mining sites (Moore & Ramamoorthy, 1984). Certain macrophytes, invertebrates, fish and mammal species have been shown to bioconcentrate zinc from sediment or from zinc released into the water above the sediment (Duke *et al.*, 1969; NRC, 1979; Seelye *et al.*, 1982; Moore & Ramamoorthy, 1984). Toxic effects depend on species susceptibility; effects on sensitive species include reduction in muscle contraction rates and reproductive impairment in crustaceans, coagulation or precipitation of gill mucus in certain fish, and a loss of oxygen to the tissues, anemia, poor bone mineralization, and arthritis or joint lesions in mammals (NRC, 1979).

Hydrocarbons and metals other than those studied, such as mercury and cadmium, are sometimes associated with drilling effluents, and may also be present at the study sites. Given the migratory nature of nearshore arctic marine species and the species-specific nature of the response to specific contaminants, further study of biota will be needed to actually evaluate biological impacts.

Continued monitoring is needed to determine the residence time of contaminants at drilling effluent disposal sites. In addition, existing criteria for regulating the discharge of drilling effluents (i.e. EPA's

National Pollutant Discharge Elimination System) in or over shallow Arctic waters should be broadened to consider other site factors, particularly circulation. The frequency of storm events and the discharge site's exposure to wave action or surges may also need to be considered when determining the rate of dispersal. Much of the Arctic coast can be considered a low-energy environment; therefore, dispersion or dilution at some sites may be insufficient every year to reduce contaminant levels to the point where biological effects are avoided.

The rapid reduction of sediment contamination becomes more important as exploration drilling involving one to three wells at a site is replaced by development drilling which may require more than 100 wells in a single location. The recent Endicott Development near Prudhoe Bay will ultimately include 120 wells drilled over a six year period, and their effluents will be discharged into marine waters less than 4 m in depth. Although the exposure of this site may ensure timely dispersal, future offshore production sites may not be so fortuitously located.

CONCLUSIONS

Based on low under-ice currents, stratification, and a resulting hyper-saline bottom layer at the end of winter, Newbury (1979) predicted poor dispersion of trace metals from drilling effluent discharges around nearshore oil production facilities in the Beaufort Sea. Although this prediction has not been verified at moderate- to high-energy sites, our findings demonstrate that, in some cases, the constituents of drilling effluents remain at concentrations well above background, in low-energy Arctic marine environments, for several years following drilling.

Persistence of toxic metals may lengthen exposure times to benthic invertebrates, their avian predators, and other trophic levels. Bio-assimilation will depend on valence state, synergistic and antagonistic interactions between metal species, and the organisms in question. More detailed biological studies will be needed to evaluate this potential.

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